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Data assimilation for three-dimensional flow monitoring in non-flat composite structures during vacuum-assisted resin transfer molding: A numerical study

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ABSTRACT

This study set out to investigate the applicability of data assimilation to the monitoring of the flow of non-planar 3D shapes through the integration of visual observations with a stochastic numerical simulation of the resin flow in a vacuum-assisted resin-transfer molding process. First, we investigated the effect of the image resolution on the flow-monitoring estimation performance. By means of numerical experiments using images of various resolutions, we verified the applicable range of the image resolution in the proposed technique. Furthermore, the proposed technique was applied to 3D structures such as curved surfaces or ribbed structures. Using the visual observation values, the impregnation distances obtained from the image data were calculated in combination with the shape of the molding. The results confirmed that our proposed method is capable of successfully estimating the 3D impregnation behavior and permeability fields.

1. Introduction

In resin transfer molding (RTM) and vacuum-assisted RTM (VaRTM), fluid resin is injected into a fibrous material, making it suitable for the integral molding of fiber-reinforced plastic (FRP), and is used for the molding of complex structures, including wind turbine blades, aircraft, and automobiles [1–5]. However, resin flow in fabric is complex for these kinds of shapes and potentially can result in molding defects, such as voids, dry spots, or weld lines, along with the a reduction in the quality of molded parts [6–8]. To control these molding defects, it is necessary to ascertain the degree of resin impregnation. Regarding the permeability measurements, the benchmark exercises were investigated by institutions around the world [9,10], and the measurement procedures for determining the average permeability of fabrics have been established. However, permeability is a global value, and it is not considered when measuring the local variations in the permeability, instead being limited to in-plane permeability measurements. This limitation of global and in-plane permeability has been described in many studies [11–13].

Numerical simulation has been used to replicate these resin behaviors in the molding process, and molding conditions have been designed that use optimization, etc. to avoid the occurrence of molding defects [14–16]. However, this type of approach is unable to deal with changes in the resin flow path, as the variation in the fabric arrangement is uncertain and difficult to control [17]. Studies have therefore employed the statistical modeling of permeability coefficients and applied these to numerical simulations [18–21]. However, although numerical simulation using these kinds of models is believed to reduce molding defects and contribute to average quality improvement, it is not capable of reliably controlling molding defects. To more effectively control molding defects, it is necessary to adaptively amend the molding conditions in response to variations in the resin impregnation paths.

With the goal of attaining this kind of void reduction, studies of flow monitoring have been conducted, wherein the resin behavior is observed using optical and electrical sensors, and the resin-impregnation behavior is reconstructed through numerical simulation [22–26]. Ascertaining the resin-impregnation states allows the control of the molding conditions, so that molding defects can be kept in check [27]. Swan et al. [28] investigated the automation of RTM for manufacturing large composite yachts by performing monitoring using infrared sensors to identify the presence of resin and adjusting the resin flow in real-time to mitigate flow front variation. Wei et al. [29,30] investigated a means of flow front control based on the estimation of the permeability/porosity ratio using a radial basis function network meta-model to predict the position of the future flow front. However, it is limited to one-directional flow, and the thickness scale is neglected. However,

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embedding the sensors presents a risk of reducing the mechanical properties. If, on the other hand, the sensors are not embedded, the measurements are restricted to the surfaces of the molded parts, making it impossible to monitor the three-dimensional (3D) resin impregnation occurring in complex shapes. For this reason, Murata et al. [31] proposed a 3D flow-monitoring technique whereby the capacitance is measured with plate electrodes, rather than having to embed sensors. The technique does not use the measurement data as is but rather employs data assimilation, where the data are expanded through combination with numerical simulation. However, a measuring system that requires the installation of multiple electrodes is cumbersome, which can be a barrier to its use. To resolve the complexity of such a measurement system, Matsuzaki et al. [32] proposed a flow-monitoring technique that uses a camera to measure the impregnation distance of the flow front on the surface of a molding and employs data assimilation to integrate these data into a numerical simulation. However, when applied to nonplanar shapes with 3D shapes, the resolution of the image data changes with the impregnation of the resin. This could lead to variations in the estimation performance in flow monitoring during the resin-impregnation process.

This paper proposes a flow-monitoring technique that uses data assimilation to merge measurement data from the surface of the molding, as well as VaRTM resin-impregnation simulation. The technique can be applied to nonplanar 3D shapes such as curved surfaces and ribbed structures. Nonplanar shapes differ from planar shapes in that the angle formed by the recording direction of the camera and the measured surface changes locally with resin impregnation, yielding the difference between the impregnation distance in the image data and the actual impregnation distance, as well as a locally variable image data resolution. This kind of variation in the resolution leads to a reduction in the measuring performance and affects the estimation in flow monitoring. The present study aims to determine the resolution conditions that can be applied to nonplanar shapes by clarifying the relationship between the resolution of the measured image and the flow-monitoring estimation performance. For the visual observation values, the impregnation distance measured from the image data are not used as is but are calculated in combination with the shape of the molding. The most significant improvements offered by the present technique compared with conventional flow monitoring are that the observation values are appropriately processed in combination with nonplanar shapes and that the applicable range of resolution in the proposed technique is clarified.

2. Flow monitoring based on data assimilation

2.1. Numerical experiment—overview

An outline of the flow-monitoring technique used in the present study is illustrated in Fig. 1(a). Camera measurements of the resin-impregnation behavior on simple molding surfaces and the resin influx into the fabric are treated as observation values. By integrating, through data assimilation, these observation values with the stochastic resin-impregnation simulation, which considers the instability of the molding conditions in VaRTM, the 3D resin impregnation behavior can be logically reconstructed.

Furthermore, the usefulness of the proposed flow-monitoring method is verified in a numerical experiment. When the method is applied, as shown in Fig. 1(b), the resin-impregnation behavior is measured using images captured with a camera, with the resin impregnation behavior observed in the experiment taken as the true values (estimation target). The resin impregnation is then estimated by combining the measured data with the results of the numerical simulation.

In contrast, in a numerical experiment, a numerical simulation is performed using known model parameters, and the values obtained from the simulation are taken as the true values. The simulated results of the true values are generated using a visualization software and measured from the recorded images. The simulation of the true values is then reconstructed by combining the observation values with the unknown numerical simulation. In the numerical experiment, the true values are simulated using numerical simulation, thus simplifying error evaluation. Thus, the applicable range of the proposed technique is verified.

2.2. Resin impregnation behavior measurement for nonplanar surfaces

For the measurements performed in the present experiment, VaRTM resin impregnation was photographed, as illustrated in Fig. 2(a). Using these images, the distance r_t^i from the resin inlet to the flow front is measured over several points. Moreover, the minimum resin mass Δm_t was measured as the photography was being performed. In this way, the observation vector $\mathbf{y}_t$ is obtained:

$$\mathbf{y}_t = \begin{pmatrix} r_t^1 & \cdots & r_t^M & \Delta m_t \end{pmatrix}^T, \tag{1}$$

where M is the observation value at the flow front.

Furthermore, if the measured surface is flat, the resin-impregnation distance r_t^i can be measured directly from the image data, as shown in Fig. 2(b). However, if the measured surface is curved, the actual resin-impregnation distance r_t^i differs from the value measured using the image data d_t^i. The actual impregnation distance r_t^i is therefore calculated according to the impregnation distance d_t^i in the image data using the following equation. The actual distance between the resin inlet and the flow front can be calculated as the length of the arc of the surface of the molding and is expressed by the following equation:

$$r_t^i = \begin{cases} R\theta = R(\theta+\varphi) - R\varphi = R\left(\sin^{-1}\frac{l_{in}}{R} - \sin^{-1}\frac{l_{in}-d_t^i}{R}\right) & \text{if} \quad d_t^i \leqslant l_{in} \\ R\theta = R(\theta-\varphi) + R\varphi = R\left(\sin^{-1}\frac{l_{in}}{R} + \sin^{-1}\frac{d_t^i-l_{in}}{R}\right) & \text{otherwise} \end{cases}, \tag{2}$$

where R is the radius of curvature of the molding, $2l_{in}$ is the distance between the endpoints of the observed surface, θ is the angle formed by the inlet point and the flow front (∠AOB in Fig. 2(b)), and φ is ∠BOC in Fig. 2(b).

Furthermore, uneven surfaces such as ribbed structures differ from flat surfaces in that it is impossible to obtain a side view by taking images from above and below, and the estimation of performance is thought to decrease (Fig. 2(c)). It is possible to increase the measuring area for these kinds of structures without increasing the number of cameras, by taking oblique images, as shown in (Fig. 2(c)). Here, the measured value r_t^i is calculated according to the measured value d_t^i in the image data, in the same way as for a curved surface, using the following equation:

$$r_t^i = \begin{cases} \frac{d_t^i}{\cos\phi} & \text{on basal plate surface} \\ \frac{d_t^i}{\sin\phi} & \text{on rib surface} \end{cases}, \tag{3}$$

where ϕ is the shooting angle of the camera. For r_t^i and d_t^i, the distance from the impregnation starting point is measured for each observed surface (Fig. 2(d)).

The observation equation expressing the linear relationship between the observation values measured as previously described and the fill fraction in the numerical simulation can be given as follows.

$$\mathbf{y}_t = \mathbf{Hf}_t \tag{4}$$

This observation equation is used to integrate (through data assimilation) the measured observational values into the fill fraction representing the resin-impregnation behavior in the numerical simulation.